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Randal D. Koster, Editor

Observation-Corrected Precipitation for the SMAP Level 4 Soil Moisture (Version 6) Product and the GEOS R21C Reanalysis

Rolf H. Reichle and Qing Liu

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1 Introduction

Simulated precipitation from atmospheric models is subject to considerable errors in volume, timing, and intensity (Gehne et al. 2016; Beck et al. 2017; Sun et al. 2018). These precipitation errors cause errors in simulated land surface hydrology, including soil moisture, shallow groundwater, and surface turbulent fluxes, which can in turn adversely impact the simulation of the atmospheric boundary layer and subsequent precipitation (Seneviratne et al. 2010; Santanello et al. 2018). To mitigate errors in the simulated land surface hydrology, observation-corrected precipitation estimates have been used to force the land surface in a variety of applications of the Goddard Earth Observing System (GEOS) model, beginning in 2011 with the MERRA-Land supplemental product of the Modern-Era Retrospective analysis for Research and Applications (MERRA; Rienecker et al. 2011; Reichle et al. 2011). Observation-corrected precipitation is also used in current GEOS data products, including Version 2 of MERRA (MERRA-2; Gelaro et al. 2017; Reichle et al. 2017a), the GEOS seasonal forecasting system (Molod et al. 2020), and the Level 4 Soil Moisture (L4_SM) product of the NASA Soil Moisture Active Passive (SMAP) mission (Reichle et al. 2017b,c, 2019, 2021).

The observations-based precipitation data products used here combine measurements from a variety of satellite instruments and/or precipitation gauges into global estimates of precipitation. Hereinafter, we refer to these products simply as "observations". The corrected precipitation datasets are derived by disaggregating publicly available, global precipitation observations from daily (or pentad) totals to hourly accumulations using background precipitation estimates from the GEOS atmospheric data assimilation system. Depending on the specific combination of the precipitation observations and the GEOS background estimates, the observations may also be downscaled in space. For example, Figures 1 and 2 of Reichle et al. (2017a) provide a schematic of the MERRA-2 precipitation corrections.

The datasets and methods used to derive corrected land surface precipitation forcing for the above-mentioned GEOS applications are well documented (Reichle and Liu 2014; Reichle et al. 2017a,b,c). The primary observations data source used in the existing applications has been the NOAA Climate Prediction Center (CPC) Unified Gauge-Based Analysis of Global Daily Precipitation (CPCU) (section 2.1.1), which is available with a relatively short (~2-day) latency. In recent years, however, shortcomings of the CPCU product have become clearer, especially in regions where the gauge network is sparse, including much of South America, Africa, and Australia (Reichle et al. 2021). For example, the CPCU product was originally used in MERRA-Land to correct precipitation across the globe, including in Africa. Owing to the sparse gauge coverage there, however, MERRA-2 switched to the CPC Merged Analysis of Precipitation (CMAP) product in Africa (Reichle et al. 2017a), and Versions 1-5 of the SMAP L4_SM algorithm did not use precipitation corrections in Africa at all (Reichle et al. 2017b). Furthermore, validation of the L4_SM product revealed very poor CPCU performance in central Australia (Reichle et al. 2017c, 2021). Moreover, the number of gauges underpinning the CPCU product has been declining in many regions of the world (Reichle et al. 2017a). Over the past two years, routine monitoring of MERRA-2 runoff estimates revealed that isolated bad data values in the CPCU product occurred in South America, Africa, and Eurasia.

Meanwhile, the NASA Global Precipitation Measurement (GPM) mission has been providing increasingly mature, quasi-global precipitation datasets through the release of the Integrated Multi-satellitE Retrievals for GPM (IMERG; Huffman et al. 2019a,b; Tan et al. 2019) suite of products (section 2.1.3). IMERG products are available either as satellite-only precipitation estimates with short (<1 day) latency or as higher-quality satellite-gauge estimates with a latency of 3-4 months.

To address the shortcomings of the CPCU data and take advantage of the IMERG products, the observation-corrected precipitation used in the latest SMAP L4_SM (Version 6) product is primarily based on IMERG data. Similarly, the forthcoming GEOS Reanalysis of the 21st Century (R21C) will be using primarily IMERG-based precipitation corrections. An important aspect of using IMERG observations to correct the simulated precipitation forcing is that it entails a distinction between retrospective and forward processing periods in the GEOS applications (section 3). Finally, in R21C and all recent L4_SM versions, both the precipitation observations and the background datasets are scaled to a common, IMERG-based, seasonally varying precipitation climatology, prior to determining the daily (or pentad) corrections. This climatological scaling was applied only partly or not at all in the precipitation corrections for MERRA-2 and older GEOS applications.

The main objective of the present Technical Memorandum is to document these changes in the precipitation corrections for GEOS applications, with a focus on SMAP L4_SM Version 6 and R21C. Since L4_SM is a land-only product, only precipitation corrections over land (including glaciated surfaces) are discussed here. At the time of writing, it remains unclear if the aerosol wet deposition scheme in R21C will use, as in MERRAero (Buchard et al. 2016) and MERRA-2 (Gelaro et al. 2017; Reichle et al. 2017a), the corrected precipitation data, which would include precipitation corrections over the ocean. As in the earlier Technical Memorandum on GEOS precipitation corrections (Reichle and Liu 2014), the present document focuses on the technical description of the datasets and methods, leaving the investigation of the science advances to forthcoming validation reports and peer-reviewed papers. Section 2 provides an overview of the precipitation observations and GEOS background data that are used in the precipitation corrections. Section 3 explains how the corrected precipitation datasets are constructed for the SMAP L4_SM Version 6 and R21C applications. Finally, section 4 provides additional remarks on precipitation corrections in GEOS applications.

2 *Input Data Products*

2.1 Observations-Based Precipitation Data Products

This section provides details about the precipitation observations on which the GEOS precipitation corrections are based, including the CPCU product, the IMERG satellite-only and satellite-gauge products, and the Global Precipitation Climatology Project (GPCP) Version 2.2 pentad and Version 2.3 monthly products. Key attributes are listed in Table 1 and discussed below. Additional information can be found in the references.

All precipitation products used here provide complete temporal and spatial coverage over land within 60°N-60°S. Any gaps in coverage outside of 60°N-60°S do not impact R21C production or SMAP L4_SM Version 6 because of the tapering of the corrections that is applied in the high latitudes (section 3.2.4), although the gaps have some impact on the land initial conditions for R21C, which are constructed using land-only spin-up simulations without the high-latitude tapering.

2.1.1 CPCU Daily Gauge Precipitation

The CPCU product provides gauge-based estimates of daily total precipitation over global land areas (Xie et al. 2010). The data are on a 0.5° grid with grid cell centers ranging from 89.75°S, 0.25°E (bottom left corner) to 89.75°N, 359.75°E (top right corner). The CPCU "V1.0" reprocessing product covers the period 1979-2005, and the CPCU "real-time" ("RT") processing product covers the period 2006-present (http://ftp.cpc.ncep.noaa.gov/precip/CPC_UNI_PRCP/GAUGE_GLB/).

The exact definition of the 24-hour period that contributes to the daily CPCU values varies across the global grid. An ancillary data file provides this information in the form of End of Day (EOD) time (which is constant for the period of the data record). Furthermore, the CPCU data product includes information about the spatial density of the precipitation gauges that were used in the construction of each estimate.

Table 1. Overview of observational precipitation data products. "Region" indicates area with full spatial and temporal coverage. "Global land" includes large lakes and glaciated land. The IMERG and GPCPv2.2/pentad products provide only partial coverage within 30° latitude of the North and South poles.

Data Product	Region	Period	Time Step	Grid Spacing	Latency	Observations
CPCU	Global land	1979 – present	Daily	0.5°	2 days	Gauges (daily)
GPCPv2.2/pentad	60°N-60°S and global land	1979 – 2016	Pentad	2.5°	n/a	Satellites, gauges
GPCPv2.3	Global	1979 – present	Monthly	2.5°	n/a	Satellites, gauges
IMERG v06B Late Run	60°N-60°S	Jun 2000 – present	½-hourly	0.1°	14 hours	Satellites
IMERG v06B Final Run	60°N-60°S	Jun 2000 – present	½-hourly	0.1°	3.5 months	Satellites, gauges (monthly)

2.1.2 GPCP Pentad and Monthly Satellite-Gauge Precipitation

The GPCP Version 2.2 pentad (GPCPv2.2/pentad) product provides quasi-global estimates of total precipitation at 5-day (pentad) temporal resolution and 2.5° spatial resolution for 1979-2016, based on gauge observations and satellite estimates (Adler et al. 2003; Xie et al. 2003, 2011). The product has only partial coverage over the Arctic and Southern Oceans (outside 60°N-60°S).

The GPCPv2.2/pentad product is provided by NOAA CPC on a global 144-by-72 (longitude-by-latitude) grid with grid cell centers ranging from 88.75°S, 1.25°E (bottom left corner) to 88.75°N, 358.75°E (top right corner). The datasets consist of 73 pentads per year, with the first pentad covering 1 January to 5 January. The 12^{th} pentad always covers 25 February to 1 March, that is, in a leap year the 12^{th} pentad includes 6 days.

The GPCPv2.2/pentad product is a temporal disaggregation of the monthly GPCPv2.2 product, with sub-monthly variations determined using the CMAP pentad satellite-gauge product (Xie et al. 2007). The monthly totals of the GPCPv2.2/pentad product are designed to match those of the monthly GPCPv2.2 product, separately for each month and each grid cell.

The monthly GPCPv2.3 product is an updated version of the monthly GPCPv2.2 product (Adler et al. 2018) that provides complete temporal and spatial coverage. Changes include improvements in the processing of the satellite inputs and the use of an updated version of the gauge input data from the Global Precipitation Climatology Centre (GPCC). These updates primarily impact the period after 2008. Prior to 2003, the differences between GPCPv2.3 and GPCPv2.2 are minimal.

GPCPv2.3 is used in the climatological scaling of the GEOS precipitation correction algorithm (section 3.1). During the period 1980 through May 2000 (that is, before IMERG data are available), we used the older GPCPv2.2/pentad product to determine correction factors (section 3.2) because a pentad version of the GPCPv2.3 product is not available and because the differences between GPCPv2.2 and GPCPv2.3 are minimal during this period.

2.1.3 IMERG Half-Hourly and Monthly Satellite and Satellite-Gauge Precipitation

IMERG combines information from the Tropical Rainfall Measuring Mission (TRMM) satellite (2000-2014), the GPM Core Observatory (2014-present), and a constellation of microwave and infrared satellites to provide quasi-global estimates of precipitation, with full coverage between 60°N and 60°S and partial coverage within 30° latitude of the poles. The IMERG data have half-hourly temporal resolution and 0.1° spatial resolution. Daily and monthly products are also available. The data are published through the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC) (https://disc.gsfc.nasa.gov/).

Three separate IMERG data products are available: (i) The IMERG Early Run gives a quick estimate upon receiving the satellite data with the shortest latency (~4 hours). (ii) The IMERG Late Run (IMERG-Late) provides better estimates as more data arrive within ~14-hour latency. (iii) The IMERG Final Run (IMERG-Final) combines IMERG-Late with monthly gauge data to further enhance the quality, but with a much longer latency of ~3.5 months.

For the GEOS precipitation corrections algorithm, we use Version 06B of both IMERG-Late and IMERG-Final (Huffman et al. 2019c,d,e). IMERG-Final is used for retrospective processing, and IMERG-Late is used for forward processing when the latency of IMERG-Final exceeds the latency of the GEOS products that use the corrected precipitation inputs.

2.2 Background GEOS Data Products

This section provides a brief overview of the GEOS data products that are used as background estimates for the precipitation corrections. Key attributes are listed in Table 2 and discussed below. Additional details about GEOS products can be found at http://gmao.gsfc.nasa.gov/products.

The MERRA-2 reanalysis provides global, hourly precipitation data from 1980 to present. The data are posted on a global 576-by-361 (longitude-by-latitude) grid with a grid spacing of 0.625° and 0.5° in the longitude and latitude directions, respectively. Grid cell centers range from 90°S, 180°W (bottom left corner) to 90°N, 179.375°E (top right corner). MERRA-2 data are published at the NASA GES DISC with a latency of ~6 weeks (https://disc.gsfc.nasa.gov/).

Hourly precipitation data are also available from the GEOS Forward Processing (FP) system from 2015 to present in near-real time (Table 2; Lucchesi 2018). Unlike reanalysis data, the data from the FP system are generated with evolving versions of the GEOS system. Since its inception, the output from the FP system has been available on a global 1152-by-721 (longitude-by-latitude) grid with a grid spacing of 0.3125° and 0.25° in longitude and latitude, respectively. Grid cell centers range from 90°S, 180°W (bottom left corner) to 90°N, 179.6875°E (top right corner). GEOS-FP data are available online (https://fluid.nccs.nasa.gov/).

Table 2. Overview of GEOS products that provide background estimates for the corrected precipitation. All products provide global data. GEOS-FP version information is available at https://gmao.gsfc.nasa.gov/GMAO_products/NRT_products.php.

Data Product	**Period**	**Time Step**	**Grid Spacing** (Longitude-by-Latitude)	**Latency**	**Version**
MERRA-2	01/01/1980 – present	1-hourly	0.50° by 0.6250°	~6 weeks	GEOS-5.2.14
GEOS-FP	01/01/2015 – present	1-hourly	0.25° by 0.3125°	~10 hours	variable

The target precipitation variables that need to be corrected for the SMAP L4_SM application are the liquid and solid precipitation fluxes at the surface, whereas for R21C, only the corrected total precipitation estimates are needed (section 4.3). The uncorrected, model-generated precipitation estimates from the moist physics module of the atmospheric model are represented by three separate precipitation fields in the 1-hourly, time-average, 2d "int" (MERRA-2) and "lfo" (GEOS-FP) output file collections:

- PRECCU (liquid precipitation flux from convection at the surface),
- PRECLS (liquid precipitation flux from large scale processes at the surface), and
- PRECSN[O] (frozen precipitation flux at the surface).

The first two fields sum up to the total rainfall (i.e., the liquid precipitation flux) at the surface. All three fields sum up to the total precipitation flux at the surface (PRECTOT). These uncorrected precipitation data are used to generate the corrected precipitation files that are inputs for R21C and SMAP L4_SM. (The uncorrected precipitation data from MERRA-2 used here should not be confused with the precipitation variables *after* the corrected precipitation has been applied in the MERRA-2 system. The latter are written out in the MERRA-2 "lfo" file collection under the variable names PRECCUCORR, PRECLSCORR, and PRECSNOCORR.)

3 *Corrected Precipitation Data for SMAP L4_SM Version 6 and R21C*

The choice of precipitation observations and background data for a given continent and period depends on data availability and data quality. Moreover, the details of the method used to compute the daily precipitation corrections depend on the relative spatial resolutions of the selected observations and background data. Table 3 provides an overview of the input datasets and methods used to generate the corrected precipitation datasets for SMAP L4_SM Version 6 and R21C. Note that corrected precipitation data are needed from 1980 to spin up the land initial conditions for the SMAP L4_SM and R21C systems.

Prior to computing the daily (or pentad) corrections, all datasets are scaled to a common climatology (section 3.1). The details of the methods for the daily (or pentad) precipitation corrections are discussed in section 3.2.

3.1 Scaling to a Common Precipitation Climatology

The precipitation observations (Table 1) and GEOS background precipitation data (Table 2) used here each have their own, distinct climatology. To ensure climatological consistency in the corrected precipitation data, the first step of the precipitation corrections algorithm consists of scaling all input ("source") precipitation products (including observations and background data) to a common, seasonally varying "target" climatology.

Since the IMERG-Final data represent the most recent, state-of-the-art, quasi-global precipitation product, we choose the IMERG-Final climatology as the primary target for scaling and use it where and when it is available. Consequently, climatological scaling is not applied to IMERG-Final data because they are already consistent with the primary target climatology. In the high-latitudes, where IMERG-Final has only partial coverage, we use the climatology of the GPCPv2.3 product as a secondary target climatology.

The climatological scaling is based on monthly data. IMERG-Final provides a monthly dataset. (Note that in the high latitudes, the IMERG-Final monthly data differ slightly from the monthly average of the half-hourly IMERG-Final data, owing to the high-latitude coverage gaps in the half-hourly data.) GPCPv2.3 is a monthly dataset. For scaling GPCPv2.2/pentad, we use the underlying monthly GPCPv2.2 data to maintain consistency with how the other datasets are processed. MERRA-2, GEOS-FP, CPCU, and IMERG-Late monthly data are constructed through simple monthly averaging. (The gap-free MERRA-2 and GEOS-FP products conveniently provide such monthly average files.) We set the IMERG-Late monthly average to a no-data value if more than 50% of the half-hourly values in a given month are missing. CPCU data have either full temporal coverage (over global land) or none.

Table 3. Overview of precipitation corrections for SMAP L4_SM Version 6 and R21C. All observations and background datasets are scaled to the IMERG-Final/GPCPv2.3 seasonally-varying climatology prior to computing the daily (or pentad) corrections (section 3.1). Observed precipitation that is "missing" in the GEOS background is always added in the correction process (section 3.2.3). For SMAP L4_SM Version 6, linear tapering of the corrections is applied starting at 50° latitude (full corrections to observations) and ending at 60° latitude (no corrections) in the Northern and Southern hemispheres (section 3.2.4). Corrected precipitation data in the 1980s and 1990s is used for spinning up land initial conditions.

	Region	**Period**	**Observations** (section 2.1)	**Background** (section 2.2)	**Method** (section 3.2)
SMAP L4_SM Version 6	North America	1980 – May 2000	CPCU	MERRA-2	*BT*
		June 2000 – 2014			
		2015 – June 2021		GEOS-FP	*AT*
		July 2021 – present			
	Africa[&]	1980 – May 2000	GPCPv2.2/pentad	MERRA-2	*AT*
		June 2000 – 2014	IMERG-Final		*BT*
		2015 – June 2021		GEOS-FP	*BT*
		July 2021 – present	IMERG-Late		
	South America, Eurasia, Australia	1980 – May 2000	CPCU	MERRA-2	*BT*
		June 2000 – 2014	IMERG-Final		*BT*
		2015 – June 2021		GEOS-FP	*BT*
		July 2021 – present	IMERG-Late		
R21C	North America	1980 – May 2000	CPCU	MERRA-2	*B*
		June 2000 – 2021	IMERG-Final	MERRA-2[+]	*B*
		2022* – present	IMERG-Late		*B*
	Africa[&]	1980 – May 2000	GPCPv2.2/pentad	MERRA-2	*A*
		June 2000 – 2021	IMERG-Final	MERRA-2[+]	*B*
		2022* – present	IMERG-Late		*B*
	South America, Eurasia, Australia	1980 – May 2000	CPCU	MERRA-2	*B*
		June 2000 – 2021	IMERG-Final	MERRA-2[+]	*B*
		2022* – present	IMERG-Late		*B*

**Exact R21C changeover date from IMERG-Final to IMERG-Late depends on production schedule.*

[+] *R21C background precipitation may be from forthcoming GEOS-IT product, depending on production schedule.*

[&]*Over ocean, precipitation corrections are same as for Africa.*

The climatological scaling can be thought of as transforming the climatology of the source data into a merged IMERG-Final+GPCPv2.3 climatology. The latter, however, is never explicitly computed. Rather, for a given source dataset, two sets of scaling parameters are computed: one for scaling the source data to the IMERG-Final climatology (primary target), and another for scaling the source data to the GPCPv2.3 climatology (secondary target). Any missing values in the "source-to-IMERG-Final-climatology" scaling parameters are filled with the corresponding values from the "source-to-GPCPv2.3-climatology" scaling parameters. Any remaining missing values are set to unity (that is, no scaling). In this way, a spatially and temporally complete set of scaling parameters is obtained for each source dataset.

The climatological scaling parameters are based on different periods, depending on the availability and characteristics of each precipitation dataset (Table 4). Most importantly, GEOS-FP data are only available for a relatively short period, and IMERG-Late (v06B) data exhibit spurious trends before the availability of the GPM core observatory in 2014. The climatological scaling of GEOS-FP and IMERG-Late data is therefore based on a "short" period (2015-2020) for both the source and target data. For the climatological scaling of CPCU, GPCPv2.2/pentad, and MERRA-2 data, we use a "long" period (2001-2020) that matches the availability of IMERG-Final at the time of processing, with one exception. Outside of North America, CPCU data exhibit spurious trends and discontinuities after the transition to real-time processing in January 2006 (e.g., Reichle et al. 2017a). Therefore, the climatological scaling of CPCU outside of North America is based on a non-overlapping "long" period (1980-2004) of CPCU data.

In summary, a set of climatology scaling parameters is derived for each source dataset as follows:

(i) Re-grid the monthly mean values of the primary target data to the grid of the source data.
(ii) Cross-mask source and target data to months when both are available (except for scaling of CPCU outside of North America).
(iii) Compute multi-year monthly mean values of the source and target precipitation data for the periods defined in Table 4. Set to no-data value if fewer than 6 months (short period) or 10 months (long period) of data are available after cross-masking.
(iv) For each grid cell, linearly interpolate the monthly climatology to 73 pentad values for both the source climatology and (separately) the re-gridded target climatology.
(v) For each grid cell and each pentad, compute the climatological scaling factor by dividing the (re-gridded) target value by the source value. The factor is limited to the interval [0.1, 10]. The factor is set to 1 (that is, no scaling) if the source or target value is less than 10^{-4} mm/d.
(vi) Repeat steps (i)-(v) for the secondary target dataset.
(vii) Fill any no-data values in the scaling parameters to the primary target with the corresponding scaling parameters to the secondary target.

The final set of scaling factors for each source dataset consists of 73 maps, one for each pentad, that are on the same grid as the source data and provide full spatial coverage (although some values for deserts or outside 60°N-60°S may indicate no scaling). These factors are applied to the corresponding time-varying daily (or pentad) source data prior to the computation of the daily (or pentad) correction factors (section 3.2).

Table 4. Time periods used for climatological scaling of the precipitation datasets employed in the precipitation correction algorithm. See text for details.

		Dataset	Climatology Period		Comments
			Start	End	
Target	Primary	IMERG-Final ("long")	2001	2020	Maximum data availability at time of processing. For scaling of CPCU, GPCPv2.2, and MERRA-2.
		IMERG-Final ("short")	2015	2020	For scaling of IMERG-Late and GEOS-FP.
	Secondary	GPCPv2.3 ("long")	2001	2020	Match "long" period of IMERG-Final. For scaling of CPCU, GPCPv2.2, and MERRA-2 where IMERG-Final not available.
		GPCPv2.3 ("short")	2015	2020	Match "short" period of IMERG-Final. For scaling of IMERG-Late and GEOS-FP where IMERG-Final not available.
Source		CPCU	2001	2020	For scaling North America data from June 2000. Match "long" period of IMERG-Final. In North America, there is acceptable temporal consistency before and after the switch to CPCU forward-processing in January 2006.
			1980	2004	For scaling North America data through May 2000 and for South America, Eurasia, Australia. Only data from the CPCU reprocessing period (through 2004) are used, owing to temporal inconsistencies in CPCU data before and after the switch to CPCU forward-processing in January 2006.
		GPCPv2.2/pentad	2001	2020	Match "long" period of IMERG-Final. Climatology computed from monthly GPCPv2.2 data.
		IMERG-Late	2015	2020	IMERG-Late (v06B) exhibits spurious trends before the GPM core observatory becomes available, particularly in North America and Eurasia.
		MERRA-2	2001	2020	Match "long" period of IMERG-Final.
		GEOS-FP	2015	2020	Maximum data availability at time of processing.

3.2 Daily (or Pentad) Precipitation Corrections Methods

This section describes the methods used for correcting the background precipitation to the observations on a daily (or pentad) basis.

There are two main methods, A and B, that are very similar. In a nutshell, the observations and the GEOS background estimates are aggregated and re-gridded, putting them on a common grid at the daily (or pentad) time step of the observations. (IMERG products are first aggregated to daily totals.) Correction factors are then derived, separately for each (observational) time step and grid cell, such that the corrected precipitation matches the observed precipitation as closely as possible for each (observational) time step and grid cell. The two main methods differ only in one aspect – in method A, the correction factors are computed on the grid of the observations and then interpolated to the grid of the background data whereas in method B, the correction factors are directly computed on the grid of the background data.

Additional algorithmic steps include the application of latitude-dependent correction procedures (“tapering”) and the handling of the special case where precipitation was observed but is absent from the background estimates (“missing” precipitation).

The methods used here are largely identical to those of Reichle and Liu (2014; their section 3.1). For convenience and clarity, the remainder of the present section includes an edited version of their description.

3.2.1 Method A

Method A computes the correction factors on the grid of the observations. This method is used when the grid spacing of the observations is coarser than that of the background data. Separately for each day (or pentad) for which precipitation observations are available, the (hourly) background precipitation is corrected as follows:

(i) Aggregate the hourly background total precipitation (PRECTOT) to the daily (or pentad) accumulation period of the observations. (IMERG products are first aggregated to daily totals.) For corrections using the CPCU product, this involves identifying for each grid cell the 24-hour period that contributes to the given “day” according to the CPCU EOD ancillary information and assigning the EOD times to the grid of the background data using the nearest neighbor method.

(ii) Aggregate/interpolate the daily (or pentad) accumulations of the background precipitation to the spatial grid of the observations. The spatial aggregation/interpolation is mass conservative.

(iii) For each grid cell of the observational product, compute a correction factor by dividing the daily (or pentad) precipitation observation by the corresponding background total precipitation (PRECTOT). This is done separately for each grid cell and each day or pentad. If the background value is zero and/or the observation is a no-data-value, the correction factor is set to 1 (that is, no correction).

(iv) Interpolate the gridded correction factors to the background grid using the approach described in step (ii).

(v) For each day (or pentad) and for each grid cell of the background grid, multiply the background hourly values of the three precipitation components PRECCU, PRECLS, and PRECSN[O] (section 2.2) by the interpolated correction factor for that grid cell.

3.2.2 Method B

Method B is used when the grid spacing of the observations is comparable to or finer than that of the background data. For each day of the observations-based precipitation data, the correction steps are as follows:

(i) Same as step (i) of method A (section 3.2.1).

(ii) Aggregate/interpolate the daily observations to the GEOS background grid using the mass conservative approach described in step (ii) of method A.

(iii) Same as step (iii) of method A except that for method B correction factors are computed on the grid of the background data.

(iv) Does not apply in method B.

(v) Same as step (v) of method A.

3.2.3 "Missing" Precipitation

If for a given background grid cell the correction factor was set to 1 because the background accumulated (daily or pentad) precipitation was zero but the corresponding observation was non-zero, the observed precipitation that is "missing" from the background is added evenly to the three corrected hourly estimates between midnight and 3am local time. Local nighttime is chosen to avoid inconsistencies with background estimates of downward radiation at the surface. If for a given hour between midnight and 3am local time the background air temperature at the lowest model level (TLML) is below 273.15 K, the precipitation is designated as snowfall and added to PRECSN[O]. Otherwise, the precipitation is designated rainfall and added to PRECLS.

3.2.4 High-Latitude Tapering

At high latitudes, the precipitation gauge network is extremely sparse, and measuring (often solid) precipitation is in any case difficult. Therefore, the quality of gauge- and/or satellite-based precipitation observations at high latitudes is typically poor. For SMAP L4_SM, the precipitation corrections are therefore tapered with latitude such that at low latitudes the observational corrections are applied as described above but at high latitudes the “corrected” precipitation is identical to the background data, with a linear tapering of the corrections across a latitude band. Specifically, after completing step (iv) of methods A and B (sections 3.2.1 and 3.2.2), adjusted (tapered) correction factors c’ are computed from the original correction factors c as follows:

$$c' = w * c + (1 - w) * 1 \quad (1)$$

where w is a latitude-dependent weight such that w=1 for abs(latitude)≤50°, w=0 for abs(latitude)≥60°, and 0<w<1 in between (linearly interpolated). The tapered correction factors c’ are then used in step (v).

As in MERRA-2, high-latitude tapering is not applied in the corrected precipitation files that are read into R21C. Rather, the tapering is done when the ancillary corrected precipitation data are used in the atmospheric model (Reichle et al. 2017a). This allows the high-latitude land surface in R21C to see the precipitation generated by the R21C atmospheric model rather than the background precipitation from MERRA-2.

4 Additional Remarks on Precipitation Corrections in GEOS Applications

4.1 GEOS Seasonal Forecasting System

The GEOS Subseasonal-to-Seasonal (S2S) version 2 prediction system (Molod et al. 2020; Nakada et al. 2018) uses corrected precipitation forcing to prepare the land initial conditions needed for the forecasts. The land initial conditions in the S2S version 2 retrospective forecasts (1981-2016) are effectively taken from its precursor, the S2S version 1 analysis[1,2], which used corrected land surface precipitation based on CMAP observations (Reichle and Liu 2014). From 2017 to present, the land initial conditions for S2S version 2 forecasts are from the continuous integration of the S2S version 2 coupled atmosphere-ocean data assimilation system that was initialized in 2012 and applies corrected precipitation forcing over land as in MERRA-2.

4.2 Diurnal Cycle of Corrected Precipitation

By construction, the diurnal cycle of the corrected precipitation forcing follows that of the background precipitation (section 3.2). For SMAP L4_SM, this is appropriate because the modeling is limited to the land surface component. For reanalysis products, however, the diurnal cycle that is imposed by the corrected precipitation is from an atmospheric model that is usually one generation behind the model used in the reanalysis of interest. For example, the diurnal cycle of the corrected precipitation used in MERRA-2 is from the MERRA background. Similarly, the diurnal cycle of the corrected precipitation in R21C is from the MERRA-2 background. That is, any improvements in the modeling of the diurnal cycle since the last reanalysis are not incorporated into the corrected precipitation used in the most recent reanalysis.

To take better advantage of the latest improvements in diurnal cycle modeling, the complete precipitation corrections algorithm could be implemented within the reanalysis system. In this case, the corrected precipitation data would use the simulated precipitation from a short-range atmospheric model forecast. A 6-hour forecast (a.k.a. "predictor segment") is already available in GEOS atmospheric assimilation systems, as part of the atmospheric analysis. Extending this forecast to a longer lead time would create background precipitation estimates that could be merged with the observed precipitation within the cycling reanalysis system. Owing to the tight schedule for R21C, however, implementation and testing of such online precipitation corrections is left for future work.

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[1]Specifically, prior to each S2S version 2 retrospective forecast, a 5-day "spin-up" of the S2S version 2 coupled atmosphere ocean data assimilation system was initialized from the S2S version 1 analysis (Molod et al. 2020). During this 5-day "spin-up", the land surface was forced with corrected precipitation based on CMAP observations (as in the S2S version 1 analysis) while the atmosphere was constrained to that of the GEOS Forward-Processing for Instrument Teams (FPIT) system. Owing to the brevity of the spin-up period, the relevant land surface initial conditions in the S2S version 2 retrospective forecasts differ only minimally from the corresponding S2S version 1 analysis.
[2]The S2S version 1 system referenced here and in Molod et al. (2020) is identical to the "V2" S2S system discussed in Ham et al. (2014) and Reichle and Liu (2014).

4.3 Rainfall and Snowfall

The Catchment land surface model used in SMAP L4_SM and R21C requires precipitation forcing split into snowfall, large-scale rainfall, and convective rainfall. The GEOS background data used in the precipitation correction algorithm are indeed split into these three components (section 2.2). This breakdown is applied to the observed total precipitation (section 3.2).

The SMAP L4_SM system uses the rainfall/snowfall breakdown from the corrected precipitation files (that is, from the background data). This is appropriate because the L4_SM modeling is limited to the land surface component. The rainfall/snowfall breakdown from the background data was also applied in MERRA-2. For reanalysis, however, there may at times be a conflict between the simulated surface meteorological conditions and the rainfall/snowfall breakdown in the corrected precipitation forcing, which is inherited from an older modeling system. Such potential conflicts are avoided in R21C, for which only the total precipitation from the corrected precipitation file is used. The breakdown into rainfall and snowfall is determined hourly within the R21C production system by preserving that of the R21C model-generated precipitation, provided the total model-generated precipitation exceeds 0.1 mm d^{-1}. Otherwise, the breakdown into rainfall and snowfall is determined from the hourly simulated temperature of the lowest atmospheric model level using a threshold of 273.16 K.

4.4 SMAP L4_SM Version 6 and R21C Production Status and IMERG Versions

At the time of this writing, SMAP L4_SM Version 6 production is well underway, and data are scheduled for public release in November 2021. For R21C, 1-2 years of sample data have been generated and are currently under evaluation. Full production of R21C is scheduled to start in 2022. The overall approach for the R21C precipitation corrections will be as described above, but some of the details remain to be determined before R21C production gets underway. Open questions for R21C include the exact changeover date from IMERG-Final to IMERG-Late, the use of GEOS-IT instead of MERRA-2 for the background precipitation, the generation of corrected precipitation files directly on the cube-sphere grid of the R21C system, and the use of precipitation corrections over the ocean for the aerosol wet deposition scheme. The final details and any potential changes in the configuration described here will be included in forthcoming R21C documentation.

Version 7 of the IMERG suite of products is expected in 2022. Once the new IMERG version is available, we will investigate and document the impact of the version change on the SMAP L4_SM and R21C precipitation corrections.

References

Adler, R. F., and Coauthors (2003), The Version 2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979-Present), *J. Hydrometeorology*, *4*, 1147-1167, doi:10.1175/1525-7541(2003)004<1147:TVGPCP>2.0.CO;2

Adler, R. F., and Coauthors (2018). The Global Precipitation Climatology Project (GPCP) Monthly Analysis (New Version 2.3) and a Review of 2017 Global Precipitation, *Atmosphere, 9*, 138, doi:10.3390/atmos9040138.

Beck, H. E., and Coauthors (2017), Global-scale evaluation of 22 precipitation datasets using gauge observations and hydrological modeling, *Hydrol. Earth Syst. Sci., 21*, 6201-6217, doi:10.5194/hess-21-6201-2017.

Buchard, V., and Coauthors (2016), Evaluation of the surface PM2.5 in Version 1 of the NASA MERRA Aerosol Reanalysis over the United States, *Atmospheric Environment, 125*, 100-111, doi:10.1016/j.atmosenv.2015.11.004.

Gehne, M., T. M. Hamill, G. N., Kiladis, and K. E. Trenberth (2016), Comparison of Global Precipitation Estimates across a Range of Temporal and Spatial Scales, *J. Climate*, *29*, 7773-7795, doi:10.1175/JCLI-D-15-0618.1.

Gelaro, R., and Coauthors (2017), The Modern-Era Retrospective Analysis for Research and Applications, Version-2 (MERRA-2), *J. Climate*, *30*, 5419-5454, doi:10.1175/JCLI-D-16-0758.1.

Ham, Y.-G., S. Schubert, Y. Vikhliaev, and M. J. Suarez (2014), An assessment of the ENSO forecast skill of GEOS-5 system, *Climate Dynamics*, *43*, 2415-2430, doi:10.1007/s00382-014-2063-2.

Huffman, G. J., and Coauthors (2019a), NASA Global Precipitation Measurement (GPM) Integrated Multi-Satellite Retrievals for GPM (IMERG). NASA Algorithm Theoretical Basis Doc., version 06, 38 pp. Available online at https://pmm.nasa.gov/sites/default/files/document_files/IMERG_ATBD_V06.pdf.

Huffman, G. J., D. T. Bolvin, E. J. Nelkin, and J. Tan (2019b), Integrated Multi-Satellite Retrievals for GPM (IMERG) technical documentation. NASA Tech. Doc., 77 pp. Available online at https://pmm.nasa.gov/sites/default/files/document_files/IMERG_doc_190909.pdf.

Huffman, G. J., E. F. Stocker, D. T. Bolvin, E. J. Nelkin, J. Tan (2019c), GPM IMERG Final Precipitation L3 1 month 0.1 degree x 0.1 degree V06, Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC), Last accessed: 25 October 2021, doi:10.5067/GPM/IMERG/3B-MONTH/06.

Huffman, G. J., E. F. Stocker, D. T. Bolvin, E. J. Nelkin, J. Tan (2019d), GPM IMERG Final Precipitation L3 Half Hourly 0.1 degree x 0.1 degree V06, Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC), Last accessed: 25 October 2021, doi:10.5067/GPM/IMERG/3B-HH/06.

Huffman, G. J., E. F. Stocker, D. T. Bolvin, E. J. Nelkin, J. Tan (2019e), GPM IMERG Late Precipitation L3 Half Hourly 0.1 degree x 0.1 degree V06, Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC), Last accessed: 25 October 2021, doi:10.5067/GPM/IMERG/3B-HH-L/06.

Lucchesi, R., 2018: File Specification for GEOS FP. GMAO Office Note No. 4 (Version 1.2), 61pp. Available online at http://gmao.gsfc.nasa.gov/pubs/.

Molod, A., E. and Coauthors (2020), GEOS-S2S Version 2: The GMAO High Resolution Coupled Model and Assimilation System for Seasonal Prediction, *J. Geophysical Research - Atmosphere.*, *125*, e2019JD031767. doi:10.1029/2019JD031767.

Nakada, K., R. Kovach, J. Marshak, and A. Molod (2018), S2S-2_1: File Specification. GMAO Office Note No. 16 (Version 1.0), 78 pp. Available online at http://gmao.gsfc.nasa.gov/pubs/.

Reichle, R. H., and Q. Liu (2014), Observation-Corrected Precipitation Estimates in GEOS-5, NASA Technical Report Series on Global Modeling and Data Assimilation, NASA/TM-2014-104606, Vol. 35, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland, USA, 18pp. Available online at http://gmao.gsfc.nasa.gov/pubs/.

Reichle, R. H., R. D. Koster, G. J. M. De Lannoy, B. A. Forman, Q. Liu, S. P. P. Mahanama, and A. Toure (2011), Assessment and enhancement of MERRA land surface hydrology estimates, *J. Climate*, *24*, 6322-6338, doi:10.1175/JCLI-D-10-05033.1.

Reichle, R. H., Q. Liu, R. D. Koster, C. S. Draper, S. P. P. Mahanama, and G. S. Partyka (2017a), Land surface precipitation in MERRA-2, *J. Climate*, *30*, 1643-1664, doi:10.1175/JCLI-D-16-0570.1.

Reichle, R. H., and Coauthors (2017b), Assessment of the SMAP Level-4 Surface and Root-Zone Soil Moisture Product Using In Situ Measurements, *J. Hydrometeorology*, 18, 2621-2645, doi:10.1175/JHM-D-17-0063.1.

Reichle, R. H., and Coauthors (2017c), Global Assessment of the SMAP Level-4 Surface and Root-Zone Soil Moisture Product Using Assimilation Diagnostics, *J. Hydrometeorology*, 18, 3217-3237, doi:10.1175/JHM-D-17-0130.1.

Reichle, R. H., and Coauthors (2019), Version 4 of the SMAP Level-4 Soil Moisture Algorithm and Data Product, *J. Advances in Modeling Earth Systems*, *11*, 3106-3130, doi:10.1029/2019MS001729.

Reichle, R. H., and Coauthors (2021), The Contributions of Gauge-Based Precipitation and SMAP Brightness Temperature Observations to the Skill of the SMAP Level-4 Soil Moisture Product, *J. Hydrometeorology*, *22*, 405-424, doi:10.1175/JHM-D-20-0217.1.

Rienecker, M. M., and Coauthors (2011), MERRA - NASA's Modern-Era Retrospective Analysis for Research and Applications, *J. Climate*, *24*, 3624-3648, doi:10.1175/JCLI-D-11-00015.1.

Santanello, J. A., and Coauthors (2018), Land–Atmosphere Interactions: The LoCo Perspective, *Bulletin of the American Meteorological Society*, *99*, 1253-1272, doi:10.1175/BAMS-D-17-0001.1.

Seneviratne, S. I., and Coauthors (2010), Investigating soil moisture–climate interactions in a changing climate: A review, *Earth-Science Reviews*, *99*, 125-161, doi:10.1016/j.earscirev.2010.02.004.

Sun, Q., C. Miao, Q. Duan, H. Ashouri, S. Sorooshian, and K.-L. Hsu (2018), A review of global precipitation data sets: Data sources, estimation, and intercomparisons, *Reviews of Geophysics*, *56*, 79-107, doi:10.1002/2017RG000574.

Tan, J., G. J. Huffman, D. T. Bolvin, and E. J. Nelkin (2019), IMERG V06: Changes to the Morphing Algorithm, *J. Atmospheric and Oceanic Technology*, *36*, 2471-2482, doi:10.1175/JTECH-D-19-0114.1.

Xie, P., J. Janowiak, P. Arkin, R. Adler, A. Gruber, R. Ferraro, G. Huffman, and S. Curtis (2003), GPCP pentad precipitation analyses: An experimental dataset based on gauge observations and satellite estimates, *J. Climate*, *16*, 2197–2214, doi:10.1175/2769.1.

Xie P., P. A. Arkin, and J. E. Janowiak (2007), CMAP: The CPC Merged Analysis of Precipitation. In: Levizzani V., Bauer P., Turk F.J. (eds), Measuring Precipitation From Space. *Advances In Global Change Research*, *28*, Springer, Dordrecht, doi:10.1007/978-1-4020-5835-6_25.

Xie, P., M. Chen, and W. Shi (2010). CPC global unified gauge-based analysis of daily precipitation, 24th Conf. on Hydrology, Amer. Meteor. Soc., Atlanta, GA.

Xie, P., R. F. Adler, G. J. Huffman, and D. Bolvin (2011), Global Precipitation Climatology Project - Pentad, Version 2.2. NOAA National Climatic Data Center. Last accessed: 25 October 2021. Available online at https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00933.

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